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Hot Subdwarf Stars as Tracers of Binary Stellar Evolution

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Abstract. Subdwarf B (sdB) stars are core-helium burning stars with exceptionally thin hydrogen envelopes. The mechanism by which they lose their envelopes has been controversial, but the consensus is that various types of binary interactions are required for their formation, making them an excellent testing ground for binary star evolution. Theory predicts that the majority of sdBs form through stable mass transfer leading to long period binaries. But to date, while close to 100 short period sdB binary stars have been discovered, not a single post-Roche-lobe-overflow long-period system is clearly established in the literature. We will show some early results from our recent effort in detecting long-period sdB systems, and discuss how space based photometric observations can be used to detect more subdwarf binaries.

1. Introduction

One of the most important issues regarding the final evolution of stars is the impact of binarity. A rich zoo of peculiar, evolved objects are born from interaction between the loosely bound envelope of a giant, and the gravitational pull of a companion. The binary interactions are not understood from first principles, and the theoretical tracks are therefore subject to many unproven assumptions such as the efficiency of envelope ejection, the postulated increase of mass-loss prior to contact, the physical description of the common-envelope phase, the accretion efficiency onto the companion, the building of a range of chemical peculiarities, and many others. Understanding how binarity can influence stellar evolution is essential for understanding the many exotic systems that litter our galaxy, and for any attempt to extrapolate this knowledge to other galaxies. Type Ia supernovae, for instance, come from close binary stars and the UV light of elliptical galaxies is dominated by hot subdwarfs (Brown et al. 2000; Han et al. 2007).

Han et al. (2002, 2003) made a thorough binary population synthesis study of the hot subdwarfs, using all three binary formation channels that are thought to contribute significantly to the population. The three are; (1) If the subdwarf progenitor has a low mass companion, then mass transfer on the RGB is unstable, and the orbit will shrink until the envelope is ejected. The study of Maxted et al. (2001) as continued by Morales-Rueda et al. (2003) and Copperwheat et al. (2011) finds that ~50% of all sdB stars reside in short-period binary systems ($P_{\rm orb} < 10\,{\rm d}$). (2) If the companion is more massive than the subdwarf (at least at the end of mass transfer), the orbit will have expanded substantially. Such orbits are hard to measure, but the companion is easily detectable spectroscopically or from infra-red excess. Napiwotzki et al. (2004) found that more than a third of their sdB sample show the spectroscopic signature of main sequence (MS) companions, while Reed & Stiening (2004), using 2MASS photometry,

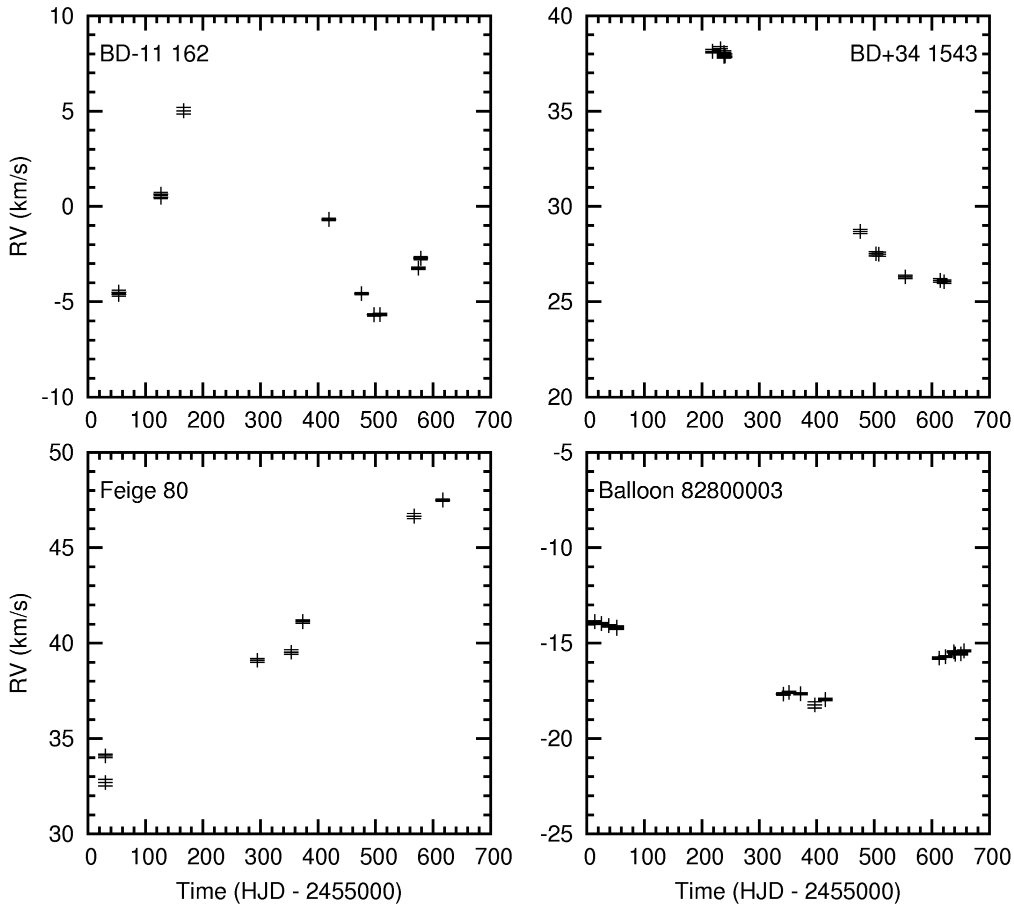

Figure 1. Radial velocity measurements for four of our sdB+F/G spectroscopic binaries. The measurements are all made with cross-correlation using the metal lines of the cool secondary.

inferred that about half of the sdBs in the field have main-sequence companions, and are therefore likely to be of this post-stable-Roche-lobe-overflow (pRLOF) type. (3) The final binary formation channel is the merger of two low-mass white dwarfs, and has a much lower efficiency than the two other channels.

By now, ~100 sdB stars are known to reside in short period binaries, and they are providing clear constraints for common-envelope ejection models. However, no detection of an orbital period for a system that must have evolved through stable Roche-lobe overflow has yet been established. Here, we report on recent progress in detecting RV variations in the sdB+F–K binaries.

2. Observations

The observations presented here were all made with the MERCATOR telescope on La Palma, which is a twin of the Swiss 1.2m Euler telescope at La Silla. In November 2008 it was furbished with a new state-of-the-art fibre-fed ultra-stable high-resolution Echelle spectrograph, dubbed HERMES (an acronym for *High Efficiency and Resolution Mercator Echelle Spectrograph,* Raskin et al. 2011). HERMES reaches a spectral resolu-

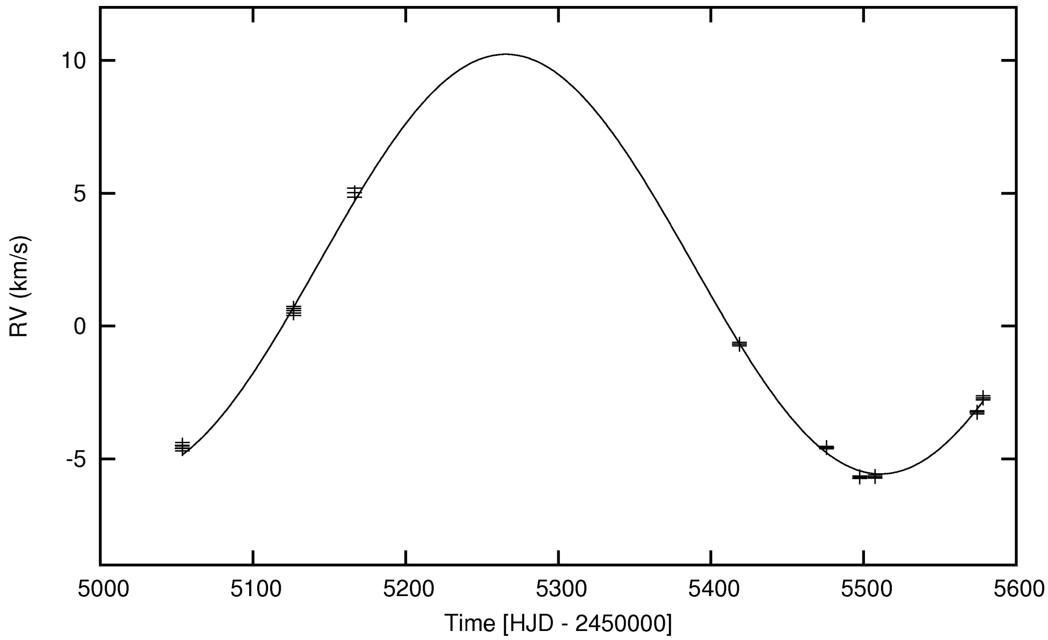

Figure 2. Thanks to the high precision of the HERMES spectrograph, the twelve observations on nine different nights of BD–11°162 are sufficient to derive a quite reliable period after just two observing seasons. The fit shown in the figure gives a period of 491 days and a velocity amplitude of 7.90±0.25 km/s for the main sequence star.

tion, $R = 85\,000$ over a spectral range covering 3770 to 9000 Å in a single exposure, and has a peak efficiency of 28%. Being mounted in a temperature and pressure controlled environment provides the stability to ensure reliable velocity determinations over extended periods of time. A substantial fraction of the observing time on MERCATOR is dedicated to a long-term program to establish orbits of evolved binary systems. Through this program we have since the first commissioning of HERMES, made regular observations of a sample of more than twenty composite hot subdwarf stars. The extreme precision and excellent time coverage provided by the HERMES spectrograph will allow us to establish the periods and velocity amplitudes of the longest period systems with very high precision.

Our long time-base spectroscopy from the Mercator telescope has revealed orbits longer than ~500 d for several sdB+F/G binaries (Fig. 1). While pRLOF systems are expected to be found with a wide range of periods, a strong peak is predicted to be found just above 100 d (see Fig. 21 of Han et al. 2003). The location of this peak is well constrained by the maximum radius the sdB progenitor can reach on the RGB. All the systems shown in Fig. 1 appear to have periods much longer than this peak.

The first example shown in Fig. 1 is BD–11°162. This binary system consists of an sdO primary with a companion of type ~G5. It was recognised to be a composite system already by Zwicky (1957). Of the four systems we show here, this one has the faintest main-sequence companion, contributing no more than 1/3 of the light in the visual part of the spectrum. Still, the cross-correlation procedure has no problem locking on to the rich metal line spectrum, and derive accurate velocities. The errors from the cross-correlation routine are less than 0.1 km/s for all the measurements. With 12

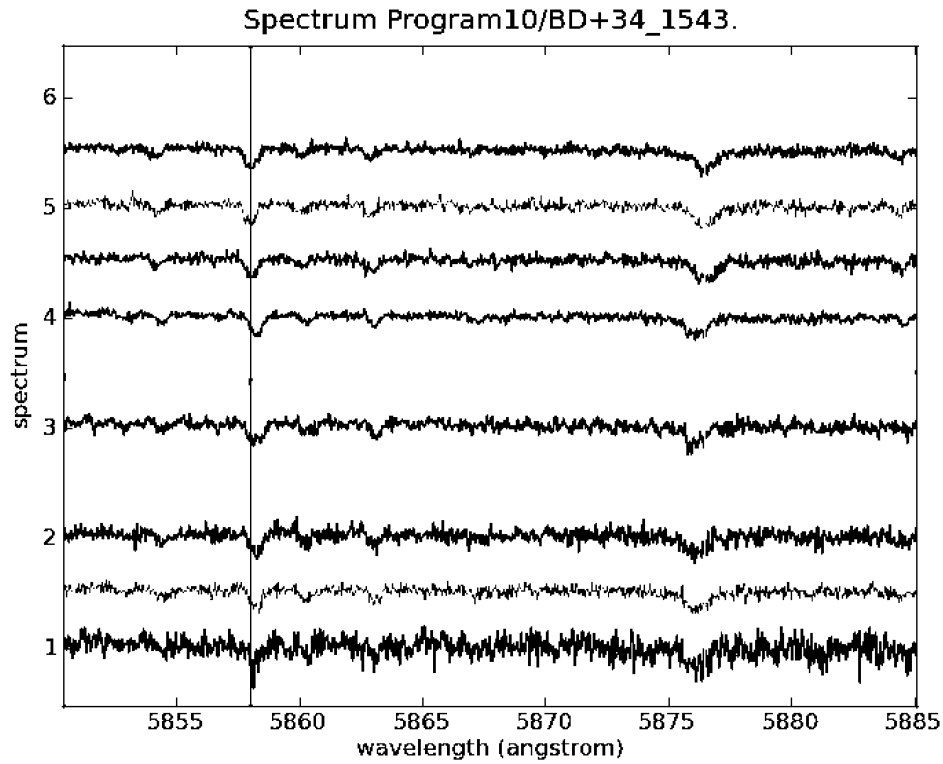

Figure 3. A small section of the eleven spectra of BD+34 1543. The He I line from the sdB at 5876 Å is clearly seen to move in the opposite phase to that of the Ca I line at 5857 Å.

observations covering more than 500 days, it appears that we have just about managed to cover a complete orbit in two observing seasons. A preliminary fit to the orbit is shown in Fig. 2, where we find that a sinusoidal orbit of 491 days and an amplitude of 7.9 km/s provide an excellent fit to the data.

The second system, BD+34°1543, was first identified as a composite sdB+F system by Berger & Fringant (1978). The He I 4472 Å line is barely detectable in the forest of lines from the cool companion, but the He I line at 5876 Å stands out clearer. The third system, Balloon 82800003 was classified as a composite by Bixler et al. (1991). As for BD+34°1543, He I 4472 is hardly detectable, but He I at 5876 Å is clearly present. Our high-resolution spectra of both these systems are completely dominated by the absorption lines from the cool secondary, which makes the velocity determination of the secondary very reliable. We have not yet made a reliable determination of the RV variability of the primary, as this is bound to be much more uncertain. In Fig. 3 we show a small section of the spectra that compose the sequence that were used for the RV determination in the upper right panel of Fig. 1. On the left side one can see the Ca I line at 5857 Å among several other weaker lines from the cool star, and on the right the He I line at 5876 Å is found. The two lines are obviously moving in antiphase with each other, and the sdB appears to have an amplitude about twice that of the F-star, as one would expect.

The final example we show here is Feige 80 (= PG 1317+123). This star is a binary with an sdO primary and an F-type companion (Ulla & Thejll 1998; Williams et al. 2001). A mean spectrum constructed from five HERMES spectra clearly reveals a strong He II 4686 line and no detectable He I, indicating a temperature in excess of 50 000 K, much higher than the 33 000 K estimate provided by Ulla & Thejll (1998). The primary is most likely in the post-EHB stage of evolution.

For all these three systems, it is clear from the RV plots in Fig. 1 that our two years of data are insufficient to cover the orbit. Balloon 82800003 might be fitted with an orbit around 800 days, but with only a minimum to show it can also be substantially longer. BD+34°1543 and Feige 80 show only a roughly constant slope indicating that the orbital period must be longer than 800 days.

3. Kepler observations of binary sdB stars

During the meeting I also presented some selected results from monitoring work done with the *Kepler* spacecraft. In these proceedings we will not go into further details regarding these results, since most of them have been presented elsewhere. For our results on searching for pulsating subdwarfs in the *Kepler* field, see Østensen et al. (2010b, 2011). The paper on the eclipsing Doppler beaming sdB+WD binary, KPD 1946+4340, is by Bloemen et al. (2011). For the spectacular sdB+dM eclipsing binary in which the hot primary shows an exceptionally rich pulsation spectrum, see Østensen et al. (2010a). Several other compact binary systems are described in Østensen et al. (2010b, 2011), including two cataclysmic variables and a DA+dM binary with a flaring secondary, all of which merit further studies.

One of the sdBs in the *Kepler* sample was found to be a short period pulsator of the V361 Hya type, and eleven were found to pulsate with the longer periods characteristic of the V1093 Her pulsators. Three of the latter are certainly in binary systems with M-dwarf companions, and the binary status of the remaining eight remains to be determined. Since asteroseismology can be used to reveal their interior composition and density profiles, this may be a great help in disentangling their evolutionary history.

4. Conclusions

Since subdwarf B stars are most likely only formed through binary stellar evolution processes including common envelope ejection, stable Roche lobe overflow and binary mergers, their study can be used to advance our understanding of these processes. For the post-mass transfer primaries that succeed in igniting helium in their cores, the core-He burning stage that lasts for more than 100 Myr provides a window of opportunity where such systems are some five magnitudes brighter than their evolutionary end-products on the white dwarf cooling curve, and bright enough to be studied with reasonably sized telescopes.

While more than one hundred hot subdwarfs are known to exist in short-period systems, the long-period systems predicted as the outcome of stable Roche-lobe overflow on the first giant branch have hitherto not been discovered. We have presented some of our first results from a dedicated survey to reveal the orbital periods of hot subdwarfs with main sequence companions, and the periods detected so far are far longer than the distribution predicted by Han et al. (2003). Some of these systems will take several more years to be finally nailed down, but the results so far are encouraging.

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